# HEMP YIELDS AND ITS ROTATION EFFECTS ON WHEAT UNDER RAINFED MEDITERRANEAN CONDITIONS


## ABSTRACT

Hemp (*Cannabis sativa* L.) has a low impact on the environment requiring few added resources, and has multiple downstream applications. There is little information on hemp biomass, seed yields, and response to NPK fertilization under humid rainfed Mediterranean conditions. Moreover, the effects of hemp on subsequent wheat (*Triticum aestivum* L.) crops have not been determined. To address these issues, we carried out a field study for 6 years in Catalonia (northeast Spain). Hemp treatments included: hemp monoculture, unfertilized hemp succeeding wheat, and NPK-fertilized hemp succeeding wheat. In turn, wheat treatments included: wheat monoculture, first-, second-, and third-yr wheat succeeding unfertilized hemp, and first-, second-, and third-yr wheat succeeding NPK-fertilized hemp. The hemp biomass yields (5340–10,090 kg $ha^{-1}$) were similar to or lower than those achieved in other European regions whereas the hemp seed yields were relatively high (604–1434 kg $ha^{-1}$). Both the biomass yield and seed yield greatly increased with NPK fertilization. The rotation effects of hemp on the subsequent wheat crops increased the wheat yield by 1368 and 155 kg $ha^{-1}$ in the first and second years, respectively, but in the third year the yield was similar to the wheat monoculture. The beneficial effects of hemp on wheat therefore appear to last for 2 years. We conclude that dual-purpose hemp (harvested for fiber and seed) is an excellent predecessor for wheat, improving the sustainability of cereal-based cropping systems under humid rainfed Mediterranean conditions.

Cropping systems in the rainfed Mediterranean region of the southern Pyrenees (northeast Spain) are mainly based on cereal monocultures such as wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), some break crops such as rapeseed (*Brassica napus* L.), and forage crops such as Italian ryegrass (*Lolium* spp.) and alfalfa (*Medicago sativa* L.) in more humid areas (Cantero-Martínez et al., 2012). The incorporation of alternative crops could improve sustainability and increase the economic viability of these cropping systems (Cosentino et al., 2013). One possibility is the reintroduction of fiber hemp (*Cannabis sativa* L.) as a break crop. Hemp was traditionally grown in the temperate Mediterranean areas of the pre-Pyrenees, with cool winters (400–900 m above sea level) and relatively humid summers (600–700 mm of annual rainfall). However, hemp cultivation in these areas declined over the 1990s due to low fiber prices, which led farmers to reduce the fertilizer rates applied. The European Union subsidy for fiber crops (over 600 € $ha^{-1}$) enabled growers to continue growing hemp until 2006, when the subsidy was abandoned due to the relocation of the hemp straw processing industry (Agrofibra SL) (Gorchs et al., 2006).

Fiber hemp is a renewable source of feed and industrial products (Struik et al., 2000, Amaducci et al., 2015). In Spain, hemp is mainly used as a raw material for the paper pulp industry (Gorchs and Lloveras, 2003), offering a more sustainable alternative to other fiber crops (Van der Werf et al., 1996). Hemp is also a promising new energy crop for conversion to bioethanol, biogas, and biomass for combustion (Zegada-Lizarazu and Monti, 2011; Amaducci et al., 2015). Furthermore, hemp is a dual-purpose crop because it can be harvested for both fiber and the valuable, nutritious seed which is mainly produced for its high-quality oil for food (Callaway, 2004; Amaducci et al., 2015). Traditionally, hemp has been grown for fiber productions, and has been harvested at the peak of flowering (male flowering in dioecious varieties) (Bocsa and Karus, 1998), when primary bast fiber yield reaches its maximum and the proportion of lignified fiber is low (Amaducci et al., 2008a). Growing hemp as a dual-purpose crop has recently gained interest when fiber or biomass are intended for uses not demanding high quality fiber (pulp for paper, bioenergy, etc.). On the other hand, little is known about the seed yield of hemp in southern Europe, which has been proposed as a suitable region for dual-purpose hemp production (Stutterheim et al., 1999). Most previous studies concerning hemp seed yields were conducted in central and northern Europe (Meijer et al., 1995; Mediavilla et al., 1999; Vogl et al., 2004; Maļceva et al., 2011, Faux et al., 2013, Delauran and Flengmark, 2005), in Mediterranean area with irrigation (Tang et al., 2016) or Canada (Girouard et al., 1999; Vera et al., 2004; Aubin et al., 2016). Moreover, residual soil nitrogen in hemp is not quantified in the bibliography to date. Evaluating it in hemp under Mediterranean conditions can facilitate the assessment of its response to N and help to improve nitrogen utilization, which is an important agronomic, economic and environmental goal in agricultural system (Zhang et al., 2015).

Fiber hemp is ideal for incorporation into cereal monocultures for four major reasons. First, it is seeded in spring with a short growing cycle (120–150 days), allowing subsequent seeding of the winter cereal (Gorchs and Lloveras, 2003). Second, it is easy to cultivate and can be grown in a wide range of environmental conditions (Gorchs and Lloveras, 2003; Zegada-Lizarazu et al., 2010). Third, it can contribute to control diseases, pests and particularly weeds (hemp has an extremely vigorous growth after emergence, which rapidly smothers weeds and allows the reduction of herbicide applications to the subsequent cereal crop) (Struik et al., 2000; Van der Werf et al., 1996; Zegada-Lizarazu and Monti, 2011). Finally, hemp improves the soil structure due to its deep root system and the large quantity of organic residues left on the ground (Amaducci et al., 2008b). It is well known that crop rotation increases yields of the subsequent crops compared to monocultures (Bullock, 1992). Nevertheless, the rotation effects of hemp on subsequent crops have not been studied in detail because of the low acreage grown with hemp (Zegada-Lizarazu and Monti, 2011). Farmers growing wheat after hemp have reported yield increases of 10–20% compared to wheat monoculture (Bocsa and Karus, 1998; Gorchs and Lloveras, 1998). The careful analysis of hemp seed yields and the rotation effects on subsequent crops is necessary to evaluate the adaptability of this crop and its potential inclusion in rainfed Mediterranean cropping systems. We therefore set out a 6-yr study to evaluate hemp biomass and seed yields under rainfed Mediterranean conditions, and to quantify the rotation effects of hemp on the subsequent wheat crops and the soil nitrate content.

## MATERIALS AND METHODS

### *Field location, soil and weather characteristics*

A field trial was conducted over 6 consecutive years (1994–1995 to 1998–1999) in a commercial field in the pre-Pyrenean area of Merlès (northeast Spain, 525 m above sea level). The soil was classified as a Typic Eutrudept (Soil Survey Staff, 2003) with a sandy-loam texture, and had the following characteristics at the beginning of the experiment (0–30 cm): pH = 8.2; organic matter (Walkley and Black, 1934) = 17 g $kg^{-1}$; P (Olsen method) = 17 mg $kg^{-1}$; and K = 211 mg $kg^{-1}$ (ammonium acetate method). The experiment was conducted under rainfed Mediterranean conditions. A weather station located in the field (Campbell Scientific Ltd, Leicestershire, UK) recorded air temperature, solar radiation and rainfall. Weather conditions are reported in Table 1.

*Experimental design and treatments*

The experiment was arranged in a randomized complete block design with four replications. The experimental field area was 80 m x 32 m (2560 $m^2$) and was seeded with sunflower (*Helianthus annuus* L.) in 1992–1993 and with wheat in 1993–1994. In 1994–1995, 32 plots were established following eight crop rotation schemes (Table 2) randomly assigned within each block. A plot was 10 m x 5 m with 2 m of border between plots, which were sown with either wheat or hemp, correspondingly. Outside the trial, the rest of the field was sown with wheat.

***Hemp treatments.*** Hemp was grown in different plots from 1994-95 to 1996-97 (Table 2). Hemp treatments included: i) unfertilized hemp after wheat (UH), ii) fertilized hemp after wheat (FH), and iii) fertilized hemp monoculture (FHM) (Tables 2 and 3). Fertilized hemp received 100, 35 and 130 kg $ha^{-1}$ $yr^{-1}$ of N [ammonium nitrate ($NH_4NO_3$), 33.5% N], P [monocalcium phosphate ($Ca(H_2PO_4)_2$, 16 % $P_2O_5$] and K [potassium chloride (CLK), 60 % $K_2O$], respectively. Note that treatment FHM was only present in 1995-96 and 1996-97 (Table 2). This design allowed to evaluate the effects of NPK fertilization on hemp production by comparing UH with FH in 1995, 1996 and 1997, as well as the effect of the preceding crop (wheat or hemp) on hemp production by comparing FH with FHM in 1996 and 1997 (Tables 2 and 3).

***Wheat treatments.*** Wheat was grown from 1994-95 to 1998-99. Wheat treatments included i) first-yr wheat following unfertilized hemp (UH1W), ii) first-yr wheat following fertilized hemp (FH1W), iii) second-yr wheat following unfertilized hemp (UH2W), iv) second-yr wheat following fertilized hemp (FH2W), v) third-yr wheat following unfertilized hemp (UH3W), vi) third-yr wheat following fertilized hemp (FH3W), and vii) wheat monoculture (WM) (Tables 2 and 3). Note that these treatments were not present each year of the study. This design allowed to evaluate the rotation effects of hemp on the three subsequent wheat crops by comparing WM plots against (i) UH1W and FH1W plots in 1996, 1997 and 1998; (ii) UH2W and FH2W plots in 1997, 1998 and 1999; and (iii) UH3W and FH3W plots in 1998 and 1999 (Table 3).

***Crop management and measurements***

***Hemp management.*** The soil was plowed with a chisel, disk and a cultivator with a roller. In fertilized hemp treatments, the fertilizer was incorporated into the soil before seeding, whereas unfertilized hemp received no NPK fertilization. Hemp was seeded between Apr. 20 and May 5, depending on the year, by using an experimental plot seeder that includes eight rows with 15 cm between rows. Seeding was carried out after rainfall (to guarantee optimal emergence) with a small tractor to facilitate the seeding of hemp plots without damaging wheat plots. The typical variety grown by farmers in the region ('Futura 77') was seeded at 350 seeds $m^{-2}$ (with over 90% viable seeds). This hemp variety is intended for fiber production, has a medium growing cycle, is monoecious (each plant bears both male and female flowers), and is maintained by Fédération Nationale des Producteurs de Semences de Chanvre (Mediavilla et al., 1999). No herbicides were used, as weeds were adequately suppressed by the crop. Similarly, no phytosanitary treatments were applied during the growing cycle, as is usual practice among hemp farmers in Spain (Gorchs and Lloveras, 2003). Hemp was sampled twice: i) for biomass at flowering (2302–2304 stage, Mediavilla et al., 1998), when fiber content and fiber quality are expected to be high, and ii) for biomass and seed yield (dual purpose) at seed maturity (2306–2307 stage, Mediavilla et al., 1998). The flowering sampling took place between Aug. 4 and 7 and the seed-maturity sampling took place between Sept. 13 and 19. In 1996, hemp could not be harvested for seed because the crop was severely damaged by a violent hail storm which occurred just after flowering sampling (Mediavilla stage 2304). About half of the stalks were broken and felt to the ground along with all leaves and inflorescences. Such severs crop damage influenced the farmer to harvest the whole field. After cutting and removing the hemp border with a bar mower, aboveground hemp biomass was determined by taking manually two subsamples of 0.6 $m^2$ (1.2 $m^2$) per plot (including four hemp rows 1 m long x 0.15 m within rows per subsample). Hemp plants in each subsample were cut at ground level with a bar mower, the number of plants was counted, and the fresh biomass was weighed. The moisture content was determined by taking and chopping 300 g of plant material from each subsample and drying at 105ºC for 24 h. The stem yield was determined by randomly selecting 5 plants per subsample (10 plants per plot), separating the stem from the leaves and the inflorescences, drying the three plant fractions at 105ºC for 24 h, and weighting them. Afterwards, the inflorescences were left about 15 days on trays in the laboratory and then the seed yield was determined by threshing the 10 inflorescences per plot using a Walter-Wintersteiger LD 180 (Ried, Austria) and drying the seeds at 105 ºC for 24 h. After picking the samples, the remaining biomass was harvested by the farmer and sold for industrial purposes.

***Wheat management***. The soil was plowed with a chisel, disk and a cultivator with a roller. Winter wheat was seeded with a cereal drill between Oct. 25 and Nov. 3, depending on the year, at 420 seeds $m^{-2}$ (viable seeds over 92%) with 15 cm between rows. Cv. 'Soissons' hard red winter type, medium-late to maturity, was chosen due to its good adaption to Mediterranean areas with relatively cold winters (Serra et al., 2012). Wheat was fertilized with 120, 35, and 110 kg $ha^{-1}$ $yr^{-1}$ of N [ammonium nitrate ($NH_4NO_3$ ), 33.5% N], P [monocalcium phosphate ($Ca(H_2PO_4)_2$, 16 % $P_2O_5$], and K [potassium chloride (CLK), 60 % $K_2O$], respectively. Nitrogen fertilizer was divided into two equal applications at Zadocks stages 21–23 (tillering) and 30 (stem elongation) (Zadocks et al., 1974). Weeds were controlled by post-applying at Zadocks stages 23-29 (tillering) 2.5 l $ha^{-1}$ of a mixture of 7.5% Ioxynil (4-hydroxy-3,5-diiodobenzonitrile), 7.5% Bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) and 37.5% MCPP (2-(4-chloro-2-methylphenoxy) propionic acid). Tralkoxidim (2-(1-(Ethoxyimino)propyl)-3-hydroxy-5-(2,4,6-trimethylphenyl)cyclohex-2-enone) was used to control wild oat (*Avena sterilis* L. subsp. *ludoviciana* and *A. sterelis,* subsp. *sterelis*) when needed (375 g $ha^{-1}$ a.i) at Zadocks stages 31-32 (stem elongation) . Wheat was harvested by hand between June 27 and July 12 by taking four subsamples of 0.9 $m^2$ (3.6 $m^2$) per plot with a hedge trimmer, and all aboveground biomass was put in a bag. In the laboratory, subsamples were weighed, the plants were threshed, and the seed was weighed. Stover was dried in the oven at 105ºC for 24 h before calculating the aboveground dry matter weight (biomass). The seed moisture content was determined from a 300-g sample using a Dickey John moisture tester (Dickey John Corp, Auburn, IL, USA). The seed yield was adjusted to 14% moisture.

***Soil nitrate content***

The soil nitrate content was determined each year after harvest at seed maturity in hemp plots, and at tillering and after harvest in wheat plots. Soil samples were taken to a depth of 90 cm in 30-cm increments using Eijkelkamp cylindrical augers (four cores per plot by each layer). Nitrates were extracted using deionized water (1:1 water to 100 g fresh soil ratio) and were measured using two Merckoquant test strips (Merck, Darmstadt, Germany) with a Nitrachek® device (Eijkelkamp, Giesbeek, Netherlands) calibrated according the standard procedure (Bischoff et al., 1996). Soil moisture content was determined by taking 5 g per subsample and drying it at 105ºC for 24 h. Nitrate concentrations were converted into kg $NO_3$-N $ha^{-1}$ by using the average apparent density from 1996 to 1998, i.e. 1430 kg $m^{-3}$.

### *Calculations*

The rotation effects of hemp on the succeeding three wheat crops were based on wheat grain yields and determined as follows: i) First-yr wheat (1996, 1997, and 1998): (UH1W – WM) for UH1W, and (FH1W – WM) for FH1W; ii) Second-yr wheat (1997, 1998, and 1999): (UH2W – WM) for UH2W, and (FH2W – WM) for FH2W; iii) Third-yr wheat (1998 and 1999): (UH3W – WM) for UH3W, and (FH3W – WM) for FH3W.

The rotation effects were expressed in kg $ha^{-1}$ of grain at 14% moisture content.

### *Statistical analysis*

Data representing the variables from every individual year and from all years together were processed by analysis of variance (ANOVA) using proc GLM, SAS v8.0 (SAS Institute, 1999). The treatments included in each analysis are shown in Table 3. Means were compared by using the protected least significant difference (LSD) ($P < 0.05$). In addition, we used a-priori orthogonal contrasts to test the impact of crop rotation on wheat yields and biomass. We grouped “UH1W and FH1W” versus “WM” for the effect of crop precedent on first-yr wheat, “UH2W and FH2W” versus “WM” for the effect of crop precedent on second-yr wheat, and “UH3W and FH3W” versus “WM” for the effect of crop precedent on third-yr wheat.

## RESULTS AND DISCUSSION

### *Hemp characterization*

***Hemp biomass and stem yield.*** At flowering, hemp biomass ranged from 5311 to 10,983 kg ha$^{-1}$ and the stem yield ranged from 3213 to 8061 kg ha$^{-1}$, depending on the year and fertilization treatment (Table 4). At seed maturity, hemp biomass ranged from 4737 to 9393 kg ha$^{-1}$, and stem yield varied between 3163 and 6386 kg ha$^{-1}$.These biomasses tended to be lower than those reported for northern Italy (Amaducci et al., 2002), southern Italy (Cosentino et al., 2013), and the Netherlands (Struik et al., 2000), probably because of the milder summer temperatures, and a more even rainfall distribution in northern European regions, and due to the irrigation in southern Italy.

On average across treatments, hemp biomass increased by 1182 kg ha$^{-1}$ between flowering and seed maturity in 1995, but decreased by 911 kg ha$^{-1}$ in 1997 (data derived from Table 4).

Hemp can lose large amounts of dry matter during the growing season (up to 3000 kg ha$^{-1}$) because leaves rapidly shed and many plants die as a result of self-thinning (Van der Werf et al., 1996), particularly under water-stress conditions such as those observed in August 1997 in our study (Table 1).

***Hemp seed yield.*** The seed yield under rainfed Mediterranean conditions averaged 1044 kg ha$^{-1}$ across years and fertilization treatments (Table 4). The seed yields obtained in this study were similar to or higher than the 300–1100 kg ha$^{-1}$ range reported in many studies conducted in central and northern Europe (Meijer et al., 1995; Mediavilla et al., 1999; Vogl et al., 2004; Delauran and Flengmark, 2005), although other studies in northern Europe achieved similar or higher seed yields (Callaway, 2004; Maļceva et al., 2011; and Faux et al., 2013). The relatively high hemp seed yields achieved in our study seems to confirm the suitability of relatively humid and rainfed Mediterranean environments for dual-purpose hemp production (stems + seeds), especially if the hemp fibers are used for paper pulp, because this industry does not require high-quality fibers.

***Fertilization of hemp with NPK.*** Fertilization of hemp with NPK significantly increased hemp biomass and stem yields in 1996 and 1997, but not in 1995 (Table 4). The lack of response to NPK fertilization in 1995 may be due to sufficient soil P (17 mg kg$^{-1}$) and K (211 mg kg$^{-1}$) levels (Villar and Aran, 2008), and possibly due to a high soil N content at sowing (data not available), given that winter and spring were dry in 1995 (71 mm from Dec. to Apr.) but wet in 1996 (412 mm) and in 1997 (240 mm).

***Effect of crop rotation on hemp production.*** The preceding crop (wheat or hemp) did not significantly affect hemp biomass, stem, or seed yields (Table 5), confirming that hemp performs well when grown in monoculture (Bocsa and Karus, 1998). However, diseases and pests can increase and fiber yields can decrease when hemp is grown in monoculture (Li, 1982). Bocsa and Karus (1998) reported that second-year and third-year hemp in monoculture requires increasing rates of fertilizer application. Our data suggest this may not always be the case, because our second-year and third-year hemp grown in monoculture had slightly higher yields than the first-year hemp after wheat at the same level of fertilizer.

***Soil nitrate content after hemp harvest.*** In each individual year, the NPK fertilization of hemp did not significantly change the soil $NO_3$-N content after harvest (compared to UH) except for the 30–60 cm layer in 1996 (Figure 1). The application of 100 kg N ha$^{-1}$ only increased the soil $NO_3$-N content (0–90 cm) by an average of 7 kg ha$^{-1}$ (33 kg N ha$^{-1}$ for UH and 40 kg N ha$^{-1}$ for FH), thus reflecting a high nitrogen use efficiency. The preceding crop (wheat or hemp) did not affect soil $NO_3$-N levels at any depth after the hemp harvest in any year (Figure 1). Over 2 years, the soil $NO_3$-N content (0–90 cm) after the hemp seed harvest averaged 42 kg N ha$^{-1}$ in the FHM plots and 46 kg N ha$^{-1}$ in the FH plots. The low soil nitrate levels observed in the FH plots after hemp harvest together with the brief period between hemp harvest and wheat sowing (1–2 months at the most) suggest a low N leaching risk for hemp production under rainfed Mediterranean conditions.

### *Wheat characterization*

***Wheat yields.*** Across wheat treatments, the average wheat grain yields were 4832, 2408, 3690 and 3063 kg ha$^{-1}$ in 1996, 1997, 1998 and 1999, respectively (data derived from Table 6). Over the last three years, yields in our study were lower than the long-term average yields for the region (4000–5000 kg ha$^{-1}$) (Cantero-Martínez et al., 2012), probably reflecting the low rainfall levels in 1998 and 1999 (Table 1) as well as the high average temperatures in May (13.6ºC in 1996, 15.4ºC in 1997, 14.2ºC in 1998, and 16.1ºC in 1999), compared to the average of 12.8ºC from 1951 to 1990. Additionally, low wheat yields in 1997 could be attributed to an extended dry period from February to May 20 (-174 mm below the 40-yr average) that reduced the number of ears (- 20 %) as well as the number of grains per ear (-33 %) (data not presented).

***Effect of hemp rotation on the subsequent wheat crops.*** Plots where first-yr wheat was preceded by hemp (UH1W and FH1W) had higher grain yields and biomass than WM plots in 1996, 1997 and 1998 (Table 6). The rotation effects of hemp on first-year wheat averaged 1368 kg ha$^{-1}$ for grain (+47%) (Table 7) and 2283 kg ha$^{-1}$ (+38%) for biomass (data not reported). Plots where second-yr wheat was preceded by hemp (FH2W and UH2W) had significantly higher grain yields and biomass than WM plots in 1997 and 1998, but had similar grain and biomass yields to WM in 1999 (Table 6). The rotation effects of hemp on second-year wheat averaged 155 kg ha$^{-1}$ (+6%) for grain (Table 7) and 431 kg ha$^{-1}$ (+8%) for biomass (data not reported). Finally, the grain and biomass yields of third-year wheat succeeding hemp (UH3W and FH3W) were similar to those of WM in both 1998 and 1999 (Table 6), suggesting the positive effect of hemp rotation on subsequent wheat crops lasts a maximum of 2 years.

This is the first study trying to quantify the rotation effects of hemp on subsequent crops. The rotation effects of hemp on wheat observed in this study are higher than the +10 to 20% estimated by farmers (Bocsa and Karus, 1998, Gorchs and Lloveras, 1998), and also higher than those reported for other crop rotations involving wheat: (i) 982 kg ha$^{-1}$ (+46%) for wheat succeeding faba beans (*Vicia faba* L.) compared to WM under rainfed Mediterranean conditions in Spain (López-Bellido et al., 1996); (ii) 400 to 600 kg ha$^{-1}$ (+15%) for wheat after canola (*Brassica napus* L.), field pea (*Pisum sativum* L.), and fallow compared to WM in a northern semi-arid climate in Canada (Arshad et al., 1998); and (iii) 500 kg ha$^{-1}$ for wheat rotated with grain sorghum (*Sorghum bicolor* L.) or fall canola against WM in Texas, USA (Unger, 2001). Our results confirm the opinion of the farmers that hemp is an excellent predecessor for wheat under rainfed Mediterranean conditions.

***Soil nitrates at wheat tillering and after wheat harvest***

Mean residual soil $NO_3$-N (0-90 cm) over the 3-year study was 39 kg ha$^{-1}$ at wheat tillering, and 54 kg ha$^{-1}$ at wheat harvest (Figure 2), ranging across years from 27 to 54 kg $NO_3$-N ha$^{-1}$ at tillering and from 40 to 72 kg $NO_3$-N ha$^{-1}$ at harvest (data derived from Figure 2). At wheat harvest, residual soil nitrate content at 0-30 cm depth was 32, 36, and 52 kg $NO_3$-N ha$^{-1}$, for 1996, 1997 and 1998, respectively. In 1998, at wheat harvest, high residual soil nitrate content at 0-30 cm might be attributed to water stress (Table 1). Indeed, in Mediterranean areas, water deficits have been reported to decrease N uptake and reduce wheat grain yield (López Bellido et al., 2005). Furthermore, high N content in hemp leaves (4 to 5% N) (Iványi and Izsáki, 2009) might have contributed to increased soil nitrate content in wheat succeeding hemp plots as a result of leaf shedding and mineralization. In addition, in Mediterranean areas, some residual nitrogen may remain as nitrate in dry years (López Bellido et al., 2005).

In first-year wheat, crop rotation did not affect soil nitrate content (0–90 cm) at tillering or at harvest (Figure 2).

Soil nitrate content at 0-30 cm depth in plots where hemp was previously grown was comparable to WM. Contrastingly, in deep soil layers (30-90 cm), plots where hemp was previously grown tended to have lower nitrate concentrations than WM (52% lower on average), which is consistent with the deep root system of hemp (Amaducci et al., 2008b). These results suggest that hemp could also play a role as a catch crop for nitrates, which is important in nitrate-vulnerable zones.

## CONCLUSIONS

The hemp biomass and seed yields in our field study ranged from 5340 to 10,090 kg ha$^{-1}$ and from 604 to 1434 kg ha$^{-1}$, respectively, regardless of the preceding crop (hemp or wheat). Fertilization of hemp with NPK significantly increased hemp biomass and stem yield without significantly increasing the soil $NO_3$-N content after hemp harvest, reflecting a high fertilizer use efficiency. Compared to wheat monoculture, the inclusion of hemp in the crop rotation increased first-year wheat yields by an average of 1368 kg ha$^{-1}$ (+47%) and second-year wheat yields by an average of 155 kg ha$^{-1}$ (+6%), but there was no yield increase in third-year wheat yields. These results suggest that the positive effect of hemp on the subsequent wheat crops lasts a maximum of 2 years. Similarly, plots where hemp was grown tended to have lower soil nitrate contents in the deep soil layers than wheat monoculture plots. This study has revealed the quantitative effects of hemp rotation on subsequent wheat crops, and confirms that dual-purpose hemp has the potential to improve the long-term sustainability of cereal-based cropping systems under rainfed Mediterranean conditions in southern Europe.

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## FIGURE CAPTIONS

**Figure 1.** Soil $NO_3$-N content (kg N $ha^{-1}$) after hemp seed harvest, for two fertilizer treatments (upper three figures) and for two crop rotations (lower two figures). Horizontal lines depict least significant differences ($P < 0.05$) at each depth when significant differences exits. Numbers within plots indicate total soil $NO_3$-N content (kg N $ha^{-1}$) from 0 to 90 cm for each treatment. ns - not significant.

**Figure 2.** Soil $NO_3$-N (kg N $ha^{-1}$) at wheat tillering (upper figures) and after wheat harvest (lower figures), for three crop rotation treatments. Horizontal lines depict least significant differences ($P < 0.05$) at each depth when significant differences exist. Numbers within plots indicate total soil $NO_3$-N content (kg N $ha^{-1}$) from 0 to 90 cm for each treatment. ns - not significant.

## TABLES

**Table 1.** Rainfall totals and average air temperatures at Merlès (Barcelona province) during each year of the field test, plus the mean historic values (1951–1990).

| | Rainfall (mm) | | | | | | Temperature (ºC) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 94-95 | 95-96 | 96-97 | 97-98 | 98-99 | Mean† | 94-95 | 95-96 | 96-97 | 97-98 | 98-99 | Mean† |
| Year | 567 | 969 | 729 | 469 | 555 | 695 | 13.2 | 12.4 | 12.7 | 12.5 | 11.8 | 11.4 |
| Wheat‡ | 158 | 560 | 388 | 320 | 283 | 336 | 9.5 | 8.5 | 8.7 | 7.7 | 6.7 | 7.2 |
| Hemp1§ | 147 | 322 | 204 | 73 | 179 | 229 | 18.7 | 17.6 | 18.2 | 18.6 | - | 16.6 |
| Hemp2¶ | 346 | 397 | 280 | 156 | 203 | 311 | 19.2 | 18.4 | 19.1 | 19.4 | - | 17.4 |

† Mean values 1951–1990 in Prats del Lluçanès, located 4 km northeast of Merlès (Barcelona province, Spain).

‡ Wheat = Nov. through May

§ Hemp 1 = May through July (harvest at flowering).

¶ Hemp 2 = May through Aug. (harvest for biomass and seed)

**Table 2.** Basic scheme of crop rotation studied for hemp (darker cells) and wheat (clearer cells) treatments and years when each treatment was present.

| | Wheat Monoculture † | Hemp-Wheat rotation ‡ | | | | | | Hemp Monoculture § |
|---|---|---|---|---|---|---|---|---|
| Year | Plot 1 | Plot 2 | Plot 3 | Plot 4 | Plot 5 | Plot 6 | Plot 7 | Plot 8 |
| 1994-95 | *W* | UH | FH | *W* | *W* | *W* | *W* | *FH* |
| 1995-96 | WM | UH1W | FH1W | UH | FH | *W* | *W* | FHM |
| 1996-97 | WM | **UH2W** | **FH2W** | UH1W | FH1W | UH | FH | FHM |
| 1997-98 | WM | UH3W | FH3W | **UH2W** | **FH2W** | UH1W | FH1W | |
| 1998-99 | WM | | | UH3W | FH3W | **UH2W** | **FH2W** | |

† *W* = wheat (not included in the comparisons). WM = wheat monoculture.

‡ UH = unfertilized hemp succeeding wheat. FH = fertilized hemp (100 kg N $ha^{-1}$, 35 kg P $ha^{-1}$, and 130 kg K $ha^{-1}$) succeeding wheat. 1W, 2W, and 3W = first, second, and third year of wheat following UH or FH.

§ *FH* = fertilized hemp (not included in the comparisons). FHM = fertilized hemp monoculture

**Table 3.** List of hemp and wheat treatments, years when each treatment was present in the study, and treatments used in each statistical analysis.

| | | Years grown | | | | | Treatments used in ANOVA | |
|---|---|---|---|---|---|---|---|---|
| Hemp treatments | Acronym | 1995 | 1996 | 1997 | 1998 | 1999 | Fertilization | Rotation |
| Unfertilized hemp | UH | X | X | X | | | X | |
| Fertilized hemp | FH | X | X | X | | | X | X |
| Fertilized hemp monoculture | FHM | | X | X | | | | X |
| Hemp treatments in a given year or in ANOVA | | 2 | 3 | 3 | | | 2 | 2 |

| | | Years grown | | | | | Treatments used in ANOVA | | |
|---|---|---|---|---|---|---|---|---|---|
| Wheat treatments | Acronym | 1995 | 1996 | 1997 | 1998 | 1999 | First-yr (1W) | Second-yr (2W) | Third-yr (3W) |
| Wheat monoculture | WM | | X | X | X | X | X | X | X |
| First-yr wheat succeeding UH | UH1W | | X | X | X | | X | | |
| First-yr wheat succeeding FH | FH1W | | X | X | X | | X | | |
| Second-yr wheat succeeding UH | UH2W | | | X | X | X | | X | |
| Second-yr wheat succeeding FH | FH2W | | | X | X | X | | X | |
| Thid-yr wheat succeeding UH | UH3W | | | | X | X | | | X |
| Third-yr wheat succeeding FH | FH3W | | | | X | X | | | X |
| Wheat treatments in a given year or in ANOVA | | 0 | 3 | 5 | 7 | 5 | 3 | 3 | 3 |

**Table 4.** Hemp biomass and stem yield at flowering, and biomass, stem, and seed yield at seed maturity, for two fertilizer treatments over three years. Hemp was grown after wheat.

| Fertilizer | Flowering† | | | | | | | | Seed maturity‡ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Biomass | | | | Stem | | | | Biomass | | | Stem | | | Seed | | |
| Treatment§ | 1995 | 1996 | 1997 | MEAN | 1995 | 1996 | 1997 | MEAN | 1995 | 1997 | MEAN | 1995 | 1997 | MEAN | 1995 | 1997 | MEAN |
| | kg dry mass (DM) $ha^{-1}$ | | | | | | | | | | | | | | | | |
| UH | 7655 | 5311 | 5340 | 6102 | 5440 | 3213 | 3848 | 4167 | 8886 | 4737 | 6811 | 5754 | 3163 | 4445 | 1063 | 604 | 833 |
| FH | 8260 | 10,983 | 10,090 | 9777 | 6265 | 8061 | 7809 | 7378 | 9393 | 8871 | 9132 | 5902 | 6386 | 6144 | 1434 | 1075 | 1254 |
| MEAN | 7958 | 8147 | 7715 | 7940 | 5853 | 5637 | 5829 | 5773 | 9140 | 6804 | 7972 | 5828 | 4775 | 5295 | 1434 | 1075 | 1044 |
| | Analysis of variance $P > F$ | | | | | | | | | | | | | | | | |
| Fertil. (F) | 0.490 | <0.001 | <0.001 | <0.001 | 0.552 | <0.001 | 0.014 | <0.001 | 0.654 | <0.001 | 0.001 | 0.920 | 0.002 | 0.039 | 0.269 | 0.105 | 0.049 |
| Year (Y) | - | - | - | 0.684 | - | - | - | 0.892 | - | - | 0.001 | - | - | 0.163 | - | - | 0.054 |
| F x Y | - | - | - | <0.001 | - | - | - | 0.002 | - | - | 0.007 | - | - | 0.055 | - | - | 0.779 |
| LSD ¶ | - | 1398 | 1457 | 815 | - | 934 | 2425 | 855 | - | 620 | 1267 | - | 1048 | 1589 | - | - | 456 |

† 2302–2304 stage (Mediavilla et al., 1998). ‡ 2306–2307 stage (Mediavilla et al., 1998). Hemp could not be harvested at seed maturity in 1996 because a hail storm damaged the crop.

§ UH = Unfertilized hemp. FH = Fertilized hemp (100 kg N $ha^{-1}$, 35 kg P $ha^{-1}$, and 130 kg K $ha^{-1}$).

¶ Least significant difference (LSD ) at $P \leq 0.05$.

**Table 5.** Hemp biomass and stem yield at flowering, and biomass, stem yield, and seed yield at seed maturity, for two rotations over two years: fertilized hemp monoculture (FHM) and fertilized hemp after wheat (FH).

| | Flowering† | | | | | | Seed maturity‡ | | |
|---|---|---|---|---|---|---|---|---|---|
| Crop | Biomass | | | Stem | | | Biomass | Stem | Seed |
| rotation§ | 1996 | 1997 | MEAN | 1996 | 1997 | MEAN | 1997 | | |
| | kg dry mass (DM) $ha^{-1}$ | | | | | | | | |
| FHM | 11,236 | 10,268 | 10,751 | 8318 | 7916 | 8117 | 9135 | 6699 | 1192 |
| FH | 10,983 | 10,090 | 10,536 | 8061 | 7809 | 7935 | 8871 | 6386 | 1075 |
| MEAN | 11,110 | 10,179 | 10,644 | 8190 | 7863 | 8026 | 9003 | 6543 | 1134 |
| | Analysis of variance $P > F$ | | | | | | | | |
| Rotation (R) | 0.713 | 0.847 | 0.704 | 0.560 | 0.927 | 0.761 | 0.674 | 0.474 | 0.528 |
| Year (Y) | - | - | 0.111 | - | - | 0.589 | - | - | - |
| R x Y | - | - | 0.9470 | - | - | 0.899 | - | - | - |
| LSD¶ | - | - | - | - - | - | - | - | - | - |

† 2302-2304 stage (Mediavilla et al., 1998). ‡ 2306-2307 stage (Mediavilla et al., 1998).Hemp could not be harvested at seed maturity in 1996 because a hailstorm damaged the crop.

§ FHM = fertilized hemp monoculture. FH = fertilized hemp succeeding wheat. In both rotations, hemp received 100 kg N $ha^{-1}$, 35 kg P $ha^{-1}$, and 130 kg K $ha^{-1}$.

¶ Least significant difference (LSD) at $P \leq 0.05$.

**Table 6.** Wheat grain yield (14% moisture content) and dry biomass yield as a function of the crop rotation: wheat monoculture (WM), first-yr wheat (1W), second-yr wheat (2W), and third-yr wheat (3W) succeeding unfertilized hemp (UH) and fertilized hemp (FH). Fertilized hemp received 100 kg N $ha^{-1}$, 35 kg P $ha^{-1}$, and 130 kg K $ha^{-1}$.

| | Grain (kg $ha^{-1}$) | | | | | Biomass (kg DM $ha^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Rotation† | 1996 | 1997 | 1998 | 1999 | MEAN | 1996 | 1997 | 1998 | 1999 | MEAN |
| | | | | | First-year wheat (1W)‡ | | | | | |
| WM | 3744b | 1683b | 3337b | - | 2921c | 8436c | 2933b | 6770b | - | 6046c |
| UH1W | 5209a | 3072a | 4211a | - | 4164b | 10,777b | 5185a | 8305a | - | 8089b |
| FH1W | 5544a | 3262a | 4437a | - | 4414a | 11,685a | 5522a | 8499a | - | 8569a |
| | | | | | Analysis of variance *P* > F | | | | | |
| Rotation (R) | <0.001 | <0.001 | <0.001 | - | <0.001 | <0.001 | <0.001 | 0.002 | - | <0.001 |
| Year (Y) | - | - | - | - | <0.001 | - | - | - | - | <0.001 |
| Y x R | - | - | - | - | 0.095 | - | - | - | - | 0.089 |
| LSD (Rotation)§ | 426 | 391 | 387 | - | 226 | 866 | 663 | 807 | - | 440 |
| Contrast ¶ | <0.001 | <0.001 | <0.001 | - | <0.001 | <0.001 | <0.001 | <0.001 | - | <0.001 |
| | | | | | Second-year wheat (2W) | | | | | |
| WM | - | 1683b | 3337b | 3164 | 2728b | - | 2933b | 6770b | 6752 | 5485b |
| UH2W | - | 1873b | 3910a | 2992 | 2924a | - | 3169ab | 8149a | 6587 | 5968a |
| FH2W | - | 2148a | 3651ab | 2726 | 2841ab | - | 3599a | 7809a | 6185 | 5864a |
| | | | | | Analysis of variance *P* > F | | | | | |
| Rotation (R) | - | 0.006 | 0.009 | 0.059 | 0.115 | - | 0.017 | 0.001 | 0.170 | 0.010 |
| Year (Y) | - | - | - | - | <0.001 | - | - | - | - | 0.001 |
| Y x R | - | - | - | - | <0.001 | - | - | - | - | <0.001 |
| LSD (Rotation) | - | 275 | 353 | - | 186 | - | 449 | 655 | - | 325 |
| Contrast | - | 0.009 | 0.006 | 0.055 | 0.059 | - | 0.025 | <0.001 | 0.170 | 0.003 |
| | | | | | Third-year wheat (3W) | | | | | |
| WM | - | - | 3337 | 3164 | 3251 | - | - | 6770 | 6752 | 6761 |
| UH3W | - | - | 3000 | 3263 | 3232 | - | - | 6080 | 7120 | 6600 |
| FH3W | - | - | 3284 | 3170 | 3227 | - | - | 6751 | 6930 | 6840 |
| | | | | | Analysis of variance *P* > F | | | | | |
| Rotation (R) | - | - | 0.112 | 0.825 | 0.589 | - | - | 0.100 | 0.550 | 0.603 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year (Y) | - | - | - | - | 0.964 | - | - | - | - | 0.390 |
| Y x R | - | - | - | - | 0.162 | - | - | - | - | 0.078 |
| LSD (Rotation) | - | - | - | - | - | - | - | - | - | - |
| Contrast | - | - | 0.187 | 0.736 | 0.501 | - | - | 0.254 | 0.352 | 0.847 |

† Fertilized hemp received 100 kg N $ha^{-1}$, 35 kg P $ha^{-1}$, and 130 kg K $ha^{-1}$.

‡ Means within a column followed by the same letter are not significantly different, according to an F-protected least significant difference (LSD) ($P \leq 0.05$).

§ Least significant difference (LSD) at $P \leq 0.05$.

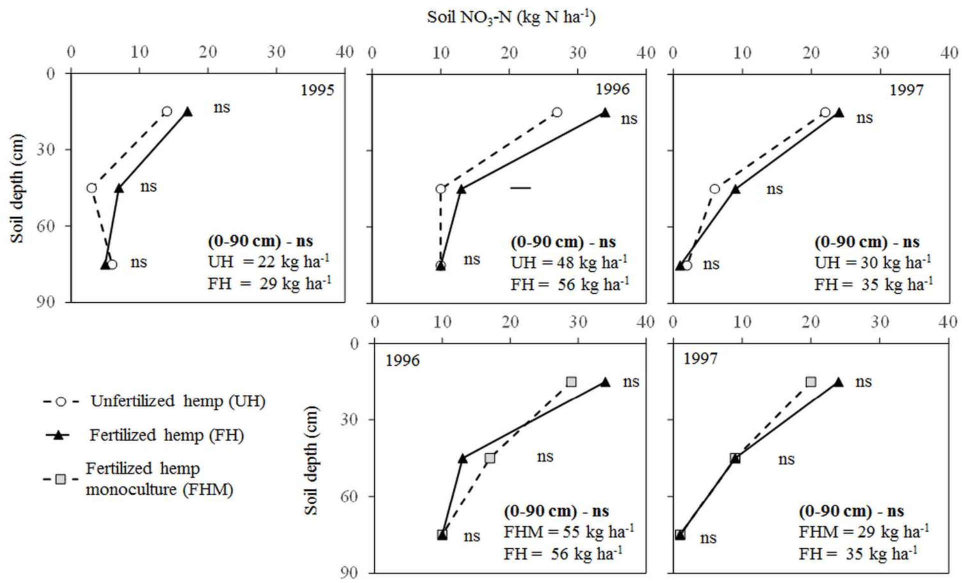
¶ Contrasts: wheat monoculture (WM) vs wheat succeeding fertilized and unfertilized hemp.

**Table 7.** Yield differences (rotation effects) of first-yr wheat (1W), second-yr wheat (2W), and third-yr wheat (3W) succeeding unfertilized hemp (UH) and fertilized hemp (FH) compared to wheat monoculture (WM).

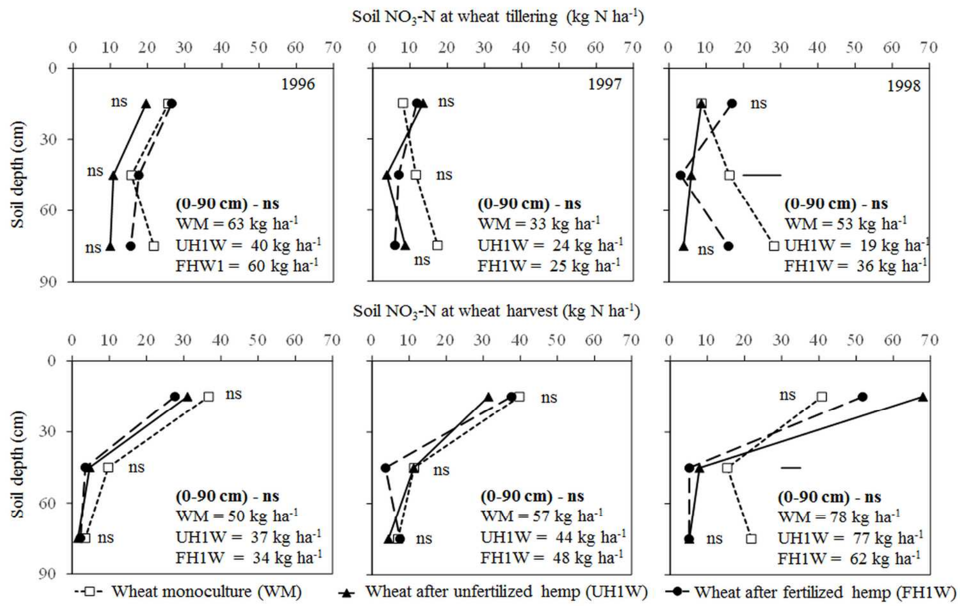
| | Rotation effect (grain yield, kg ha$^{-1}$ at 14% moisture content) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rotation† | 1996 | 1997 | 1998 | MEAN | Rotation | 1997 | 1998 | 1999 | MEAN | Rotation | 1998 | 1999 | MEAN |
| | First-year wheat (1W) | | | | | Second-year wheat (2W) | | | | | Third-year wheat (3W) | | |
| UH1W | 1465 | 1389 | 874 | 1243 | UH2W | 190 | 573 | -172 | 197 | UH3W | -337 | 99 | -119 |
| FH1W | 1800 | 1579 | 1100 | 1493 | FH2W | 465 | 314 | -438 | 114 | FH3W | -53 | 6 | -24 |
| Mean | 1633 | 1484 | 987 | 1368 | Mean | 328 | 444 | -305 | 155 | Mean | -195 | 53 | -71 |
| | Analysis of variance *P* > F | | | | | | | | | | | | |
| Rotation (R) | 0.179 | 0.334 | 0.423 | 0.062 | | 0.234 | 0.545 | 0.378 | 0.628 | | 0.341 | 0.625 | 0.554 |
| Year (Y) | - | - | - | 0.417 | | - | - | - | 0.026 | | - | - | 0.474 |
| Y x R | - | - | - | 0.874 | | - | - | - | 0.351 | | - | - | 0.262 |
| LSD (Rotation) ‡ | - | - | - | - | | - | - | - | - | | - | - | - |

† Fertilized hemp received 100 kg N ha$^{-1}$, 35 kg P ha$^{-1}$, and 130 kg K ha$^{-1}$.

‡ Least significant difference (LSD) at $P \leq 0.05$.




779x480mm (96 x 96 DPI)

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